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Comments on the Prediction of Dynamic Stall

by

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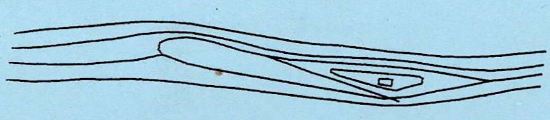

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Summary

This report contains a brief discussion on the catagories and capabilities of current methods of predicting dynamic stall. The catagories considered are similar to those of previous surveys[1,2,3], whilst the quality and capabilities of each model considered, are assessed on the basis of the currently accepted salient features of the stall[1,4], and other influential factors. The subjective assessments of the model details are concisely presented in tabular form which covers the major portion of the work. The table is intended as a quick reference guide to the models. Finally, the report concludes with a speculative discussion on future prospects.

1) Introduction

The importance of dynamic stall on the performance of a helicopter is well understood[5] and, thus, the need to possess a predictive capability for it, is evident[1-5,6]. Over the years, many schemes have been proposed and are still under continuous development. These have been surveyed[1,2,3] and a broad classification adopted whereby the different methods are grouped according to the mathematical technique, or otherwise. To date, however, no quick comparative summary of the relevant methods has been carried out. Such a summary forms the basis of this report and, inevitably, the survey will be subjective and should be treated so.

It is not the purpose of the discussion herein, to set one model against another, but simply to highlight, and roughly grade, the salient features of each and succinctly present them. The result (tab. 1) is, it is hoped, fair to all and can be usefully enhanced as the models and criticisms develop. Each of the models has been developed to fulfill a specific requirement, and any relative grading of the models (not done here) must reflect this need.

The manner in which the models will develop is inextricably linked to both the physical understanding of the stall process and the computational power and speed of the available computers. To date, there is no obvious single way to proceed and the reasons for this are discussed.

2) Survey of current methods

2.1 The model catagories and salient stall features

As with the previous surveys[1,2,3], the various models have been broadly catagorised under the following headings (tab.1, inc references).

a) Navier-Stokes methods

b) Discrete vortex methods

c) Zonal methods

d) Predominantly empirical methods

Navier-Stokes solutions, of which there are two noteable methods, attempt to solve the relevant equations in their fundamental form by numerical techniques. In contrast to this the "Discrete Vortex" approach normally ignores the viscous terms in the basic equations and assumes potential flow outwith the boundary layer. The viscous nature of the flow is modelled or taken account of, by the generation and subsequent induced transport of discrete combined vortices. The manner and location of their generation is normally obtained empirically or via appropriate boundary layer calculations. A further and related simplification of the Navier-Stokes methods is used in the "Zonal" models in which the predicted separation or viscous "zone" is taken as the boundary for the external potential flow. In the numerical procedure of the model, the regions interact in an iterative manner.

In the above three catagories, there is a distinct attempt to invoke the basic equations of fluid motion and around this philosophy the flow model is constructed. In contrast to this, the last and very broad category, considers all models in which little or no direct account is taken of the basic equations. These models rely on good quality empirical data matched to a model of the gross features of the stall process; they commonly form part of a rotor performance program.

The predictive capabilities of the considered models are, like the models themselves, catagorised and these catagories are

a) To stall onset
b) At stall onset
c) Post stall
d) Types of motion considered
e) Other factors.

Within the above, the details considered relevant are listed (tab.1) and include such events as transition, induced effects of the wake and re-attachment etc. It is assumed that all models should be capable of giving C_N and C_M predictions and so these have been excluded from the table.

If a model considered any of the listed features either explicitly or implicitly, an appropriate symbol was placed in the relevent location of table 1. These symbols were:

*	good consideration of the phenomenon
+	approximate
0	very approximate
Δ	being developed
—	not modelled.

The allocation of these symbols, based on the published work, is a most subjective process, and is not a grading of the models performance; especially with respect to C_N and C_M.

2.2 Fundamental Navier-Stokes methods

Here the two most commonly quoted works have been considered. The first, Metha[7], only considers the laminar state, but the resulting flow patterns clearly showed the characteristics which are normally associated with dynamic stall such as vortex build up, its convection and eventual shedding from the trailing edge. Figure 1 illustrates the C_L, C_M and α cycles obtained. As a consequence of the fundamental nature of the process it is accepted that a good consideration of the listed factors is as indicated, but due to the restriction of laminar flow, the Reynolds number variation is assessed as approximate. At the stall onset, both leading and trailing edge criteria are implicitly modelled.

The second such solution, Shamroth[8], takes account of turbulent flow and, in doing so, requires the inclusion of a suitable turbulent model or closure hypothesis. On the quality and appropriatness of the turbulence model and necessary empirical inputs, will the accuracy of the predictions depend, once the numerical problems have been minimised. Unfortunately, no overall C_N and C_M data were given, but the pressure distributions obtained from ramp like motions, fig. 2, are encouraging.

2.3 Discrete vortex methods

Only three of the seven listed methods (tab. 1) will be considered in detail and these are those of refs. 11, 12 and 13. The first of these, Vezza and Galbraith[11], represents the aerofoil surface by a vortex sheet from which, at the separation points, two further sheets emerge and, in time, these are replaced by discrete vortices (fig. 3). At present, the method is only applicable to trailing edge separation. So far only ramp and impulsive motions in pitch have been considered, but the oscillatory case is under development and the necessary separation and re-attachment criteria will be based, on the data of ref. 17.

In contrast to this, the model of Spalart et al[12] is highly developed and the technique employed envelopes the aerofoil in a line of discrete vortices positioned a small distance from the aerofoil surface. On this surface the zero velocity condition is invoked. The vortices may be continuously created or absorbed, and convected in the induced flow field. Initially the convection was unrestricted, but subsequently linked to a separation point obtained via a suitable boundary layer calculation. As may be seen in fig. 4, the predictions are most encouraging and consideration of an unsteady boundary layer calculation with flow reversal has been made.

The method of Lewis[13] is, as yet, only applicable to fixed incidence aerofoils, consideration is being given to the unsteady case and although it is similar to that of ref. 12, it contains an interesting "random walk" technique to account for viscous diffusion. The method is highly developed and widely applicable. For example, it is capable of giving a good reproduction of the Blasius profile for the zero pressure gradient boundary layer (see fig. 5).

2.4 Zonal Methods

The three methods considered in the survey include that of Scruggs et al[17] which is not a pure dynamic stall method. It is, however, an important contribution, in that the effects of pitch rate on flow reversal within the viscous zone/boundary layer are clearly expressed. Their results have been used, for example, by Vezza and Galbraith[11] and Beddoes[19].

The model of Rao et al[16] is a quasi-steady method which models trailing edge separation. The shape and induced effects of the wake are included by enclosing the "dead air" region within two vortex sheets lying along streamlines of the flow. The dynamic stall overshoot in C_N etc. and the hysterisis loop associated with oscillatory cases are predicted as may be seen in fig. 6.

The model of Crimi and Reeves[18] is similar to that of Rao et al, but is more general in that it includes bubble growth and bursting criteria which may be invoked depending on the boundary layer state predicted. Figure 7 shows typical results and it may be seen that, as with ref 16, several of the gross effects of dynamic stall are predicted, but the vortex induced lift is not.

2.5 Predominantly empirical

These methods, like most of the above, are well considered in refs. 1, 2 and 3. The category is, however, very large as may be realised from the very different approaches of Beddoes[19] and Gangwani[20], which are respectively, a time delay method and an apparently highly empirical and accurate curve fit.

Although the method of Beddoes is dependent on empirical time delays, it is based on, and models, accepted gross features of the dynamic stall process. It is therefore biased towards a physical interpretation of the flow, where as the method of Gangwani (synthesised approach) is predominantly empirical and borders on a pure and highly accurate curve fitting exercise. In principle, the latter could account for all the effects listed in table 1, provided sufficient good quality data were available. Both these methods are remarkably successful as may be judged from figs. 8 and 9.

A significant distinguishing feature of this catagory is, that these methods are mainly those currently used in the helicopter industry and have been developed to fulfil a particular task. They are still being developed and their predictive capability may be observed in figs. 8 to 11.

3) General Discussion

When considering the summary table, it should be recalled that it relates to the phenomena modelled and not the overall performance in predicting the time histories of C_N and C_M. If the table is used to assess predicted C_M and C_N histories, one would probably conclude that the Navier-Stokes methods, because of their comprehensive nature, would be among the best performers. Their comprehensive nature follows from the philosophy of modelling the flow via the basic equations and assuming that, in doing so, the observed flow phenomena will automatically be predicted. In this respect they are fundamentally different from all other models in which individual flow phenomena of the stall process are considered to a greater or lesser extent. Whilst, for the laminar case this may be justified, and very impressive predictions are obtained, this is primarily a consequence of having a well understood and accurate stress-strain relationship. Such accuracy is not possessed, however, by current turbulence models, and on the inginuity and applicability of the chosen hypothesis will the quality of the predicted flow development depend. To permit flow development from the basic equations employing a very approximate turbulence model, will likely result in very approximate predictions, albeit the salient features of the stall are implicitly modelled.

For the discrete vortex methods, it may be seen that, whilst the unsteady pressure distribution is normally predicted up to the stall onset, the detailed boundary layer effects are not. Spalart et al, however, did include such a calculation, but with limited success and work on the inclusion of an unsteady boundary layer method continues. The incentive for such work is, of course, to provide a suitable stall criterion. If no boundary layer assessment is included, the stall onset criterion is simply an empirical input, and thus the methods are on a par, for this salient feature, with predominantly empirical procedures. Once the stall is initiated, however, the subsequent development is well considered up to the process of re-attachment as indicated in tab. 1.

The predominantly empirical methods do not, at first sight, appear particularly favourable, but a closer inspection of tab. 1 and figs. 9 and 10 may reveal that the important stall onset and re-attachment are well considered and may even account for the effects of sweep.

From all the data presented herein, it is clear that there is a lack of comparisons between the empirical and predicted C_N and C_M histories (less so in the predominantly empirical methods) and each modeller tends to present his own personal test cases. This makes a detailed comparison difficult and suggests that there is a distinct requirement for a set of accepted and pertinent tests cases such as exists for boundary layer work (first used in 1968 at the Stanford Conference[25]). Even fewer comparisons are given for the unsteady pressure distributions, where appropriate, and such information would be useful when assessing predictive capability in detail. A set of test cases could, as it develops, cover a range of motions and the "other factors" which are little considered by all the methods.

The proposed data base implies future development of the methods; but which ones? It is suggested that this is an unanswerable question. The purist may prefer continued strong effort in the fundamental Navier-Stokes equations because, once the numerical algorithms are developed, all that remains is to improve the turbulence model. If the finite difference grid were such that the explicit modelling of the large scale turbulence could be eliminated, then the problem of the turbulence model would be simplified; but the small scale would remain. This, however, requires massive computing power and, at present, such power is unavailable and future prospects of attaining it are debatable[26,27].

In contrast to this, the predominantly empirical methods require little computer resources but numerous criteria to individually model the relevant manifestations of the stall. The more comprehensive this is, the greater the requirement for good quality empirical data, the collection of which is expensive and time consuming. In principle, however, all the factors noted in tab. 1 may be accounted for by suitable correlations to provide more general models. These would use limited computer resources and yield economic predictions when used in rotor performance codes.

There is, thus, a dilema on how to proceed. Navier-Stokes solutions require, in essence, a single closure hypothesis but large computer resources, whilst the empirical models need only limited computational power but large and expensive data bases. Unfortunately, the problem is further complicated by the prospect of a "rational" computer which will use both large computing capacity and the accumulated data bases. Such methods could possess a heuristic quality that is at present unavailable, and the desire for effective "rational" algorithms has provided the incentive to develop the necessary computers labled, 5th Generation[26].

If the above suggested codes are realised, they could be incorporated in an "integrated" package for aerofoil performance etc (eg ref. 28), and will require access to appropriate data banks and prediction procedures. In fact, all the hard earned data collected to date, would find a new use and as more was accumulated and made available they, in effect, would add to the "rational" program's "experience". There is thus the possibility that, in pursuing the further development of empirically dominated methods, the necessary collected data would have alternative uses.

4) Conclusions

It is concluded that,

1) There is a definite need for accepted test cases by which the performance of dynamic stall methods may be assessed.

2) There is a currently unresolved dilema as to which basic prediction philosophy should be adopted. Using the appropriate form of the Navier-Stokes equations in finite difference form requires large and expensive computing power, whilst the predominantly empirical procedures need little of such power but much expensive data.

3) The summary table provides a quick reference to the methods and this should be developed and modified where necessary.

Acknowledgements

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Addendum

At the time of printing the report, recent work by Maskew and Dvorak was brought to the author's attention. This is a significant development of their original method[16] and is a highly developed, hybrid between discrete vortex and the zonal methods as defined under the catagorisation. The sketch below, taken from their paper, illustrates the concept which they hope to extend to three-dimensional flows. Separation points during the aerofoil motion are obtained from an integral unsteady boundary layer procedure. As such an update to the summary table is included.

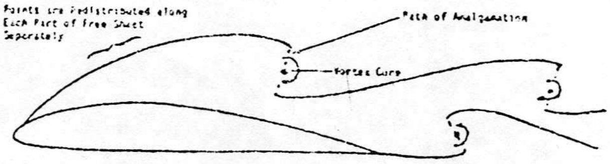

Illustration of Multiple Vortex Core Amalgamation and Redistribution Scheme.

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			UNSTEADY PRESS. DIST.	UNSTEADY BOUNDARY LAYER	LAM – TURB. TRANSITION	FLOW REVERSAL	COMPRESSIBILITY	L.E. CRITERION	TRAILING EDGE SEPARATION	SHOCK - WAVE INTERACTION	ACOUSTIC WAVES	VORTICITY BUILD-UP / SHEDDING	VORTICITY TRANSPORT	WAKE MODELLING	INDUCED EFFECTS OF WAKE	SUBSEQUENT VORTEX SHEDDING	RE-ATTACHMENT	SINUSOIDAL	RAMP	PLUNGE	OTHER	SWEEP / 3-D	REYNOLDS N°	BLADE VORTEX INTERACTION	ROUGHNESS ETC.	FREE STREAM TURBULENCE	NOISE
NAVIER STOKES	METHA	7	*	*	—	*	—	*	*	—	—	*	*	*	*	*	*	*	—	—	—	—	+	—	—	—	—
	SHAMROTH	8	*	*	*	*	*	*	*	—	—	*	*	*	*	*	*	—	*	—	—	—	—	—	—	—	—
DISCRETE VORTEX	HAM	9	+	—	—	—	—	O	—	—	—	*	*	*	*	—	+	*	—	—	*	—	—	—	—	—	—
	BAUDU	10	*	—	—	—	—	+	—	—	—	*	*	*	*	*	—	*	—	—	—	—	—	—	—	—	—
	VEZZA	11	*	—	—	—	—	—	O	—	—	*	*	*	*	*	Δ	*	*	Δ	*	—	—	—	—	—	—
	SPALART	12	*	Δ	+	Δ	—	+	+	—	—	*	*	*	*	*	+	*	—	—	—	—	—	—	—	—	—
	LEWIS	13	*	—	—	—	—	+	+	—	—	*	*	*	*	*	—	Δ	—	—	O	—	O	—	—	—	—
	ONO	14	*	—	—	—	—	O	O	—	—	+	*	*	*	+	+	*	—	*	—	—	—	—	—	—	—
	KATZ	15	O	—	—	—	—	O	O	—	—	*	*	*	*	*	—	—	—	—	+	—	—	—	—	—	—
ZONAL	RAO	16	O	O	*	—	—	—	*	—	—	—	—	O	O	—	+	*	—	—	—	—	—	—	—	—	—
	SCRUGGS	17	*	*	—	*	—	—	*	—	—	—	—	—	O	—	—	—	*	—	—	—	—	O	—	—	—
	CRIMI	18	+	O	*	—	—	*	*	—	—	—	—	O	O	—	*	*	*	*	*	—	—	O	—	—	—
PREDOMINANTLY EMPIRICAL	BEDDOES	19	+	—	—	—	*	*	*	*	—	*	*	—	—	—	*	*	*	—	—	—	—	—	—	—	—
	GANGWANI	20	—	—	—	—	*	*	—	—	—	*	*	—	—	—	*	*	—	*	*	*	O	—	—	—	—
	TRAN	21	—	—	—	—	*	O	O	—	—	O	O	—	—	—	*	*	—	+	—	*	—	—	—	—	—
	ERICSSON	22	—	—	—	—	O	O	O	—	—	—	—	—	—	—	+	*	*	*	—	—	—	—	—	—	—
	GORMONT	23	—	—	—	—	*	O	—	—	—	—	O	—	—	—	+	*	—	—	—	—	—	—	—	—	—
	JOHNSON	24	—	—	—	—	—	O	—	—	—	—	*	—	—	—	O	—	*	—	—	—	—	—	—	—	—

* GOOD CONSIDERATION. + APPROXIMATE. O VERY APPROXIMATE. Δ BEING DEVELOPED. — NOT MODELLED.

TABLE 1

METHOD FOR PREDICTIONS / PREDICTIVE CAPABILITY		REF.	TO STALL ONSET					STALL ONSET				POST STALL						MOTION				OTHER FACTORS					
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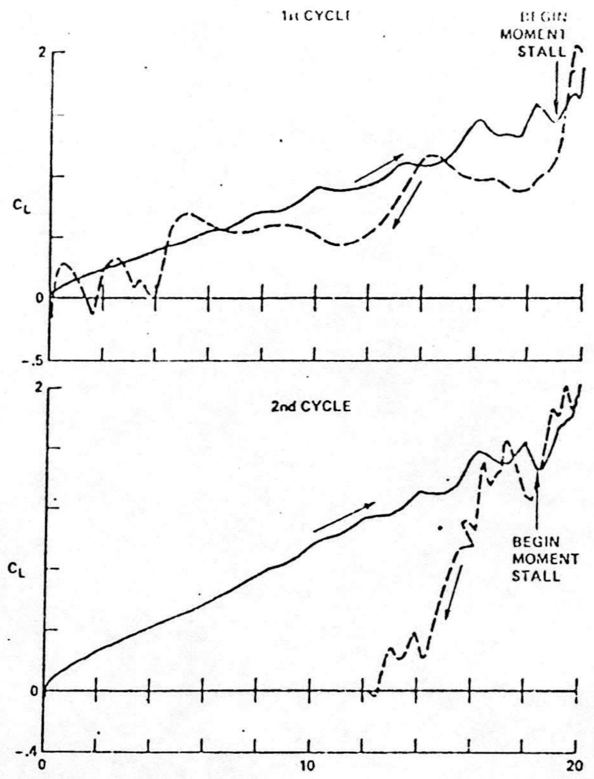
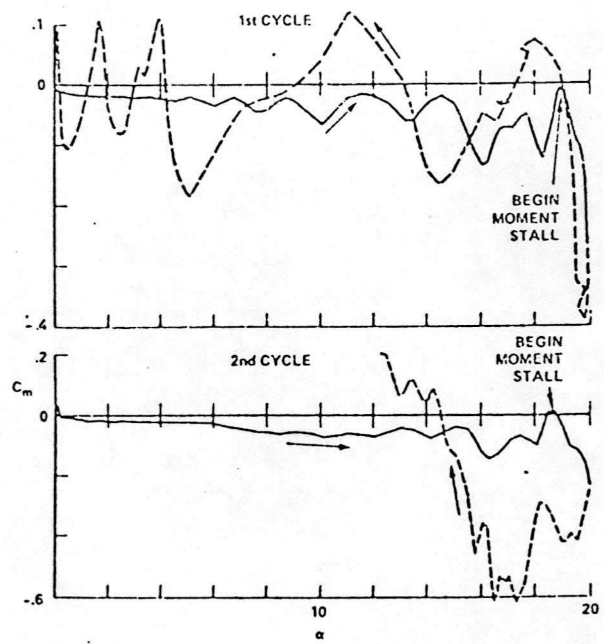
NAVIER STOKES	METHA	7	*	*	—	*	—	*	*	—	—	*	*	*	*	*	*	*	—	—	—	—	+	—	—	—	—
	SHAMROTH	8	*	*	*	*	*	*	*	—	—	*	*	*	*	*	*	—	*	—	—	—	—	—	—	—	—
DISCRETE VORTEX	HAM	9	+	—	—	—	—	O	—	—	—	*	*	*	*	—	+	*	—	—	*	—	—	—	—	—	—
	BAUDU	10	*	—	—	—	—	+	—	—	—	*	*	*	*	*	—	*	—	—	—	—	—	—	—	—	—
	VEZZA	11	*	—	—	—	—	—	O	—	—	*	*	*	*	*	Δ	*	*	Δ	*	—	—	—	—	—	—
	SPALART	12	*	Δ	+	Δ	—	+	+	—	—	*	*	*	*	*	+	*	—	—	—	—	—	—	—	—	—
	LEWIS	13	*	—	—	—	—	+	+	—	—	*	*	*	*	*	—	Δ	—	—	O	—	O	—	—	—	—
	ONO	14	*	—	—	—	—	O	O	—	—	+	*	*	*	+	+	*	—	*	—	—	—	—	—	—	—
	KATZ	15	O	—	—	—	—	O	O	—	—	*	*	*	*	*	—	—	—	—	+	—	—	—	—	—	—
ZONAL	RAO	16	O	O	*	—	—	—	*	—	—	—	—	O	O	—	+	*	—	—	—	—	—	—	—	—	—
	MASKEW		*	*	+	—	—	*	*	—	—	+	Δ	Δ	Δ	—	O	*	*	—	—	Δ	—	—	—	—	—
	CRIMI	18	+	O	*	—	—	*	*	—	—	—	—	O	O	—	*	*	*	*	*	—	—	O	—	—	—
PREDOMINANTLY EMPIRICAL	BEDDOES	19	+	—	—	—	*	*	*	*	—	*	*	—	—	—	*	*	*	—	—	—	—	—	—	—	—
	GANGWANI	20	—	—	—	—	*	*	—	—	—	*	*	—	—	—	*	*	—	*	*	*	O	—	—	—	—
	TRAN	21	—	—	—	—	*	O	O	—	—	O	O	—	—	—	*	*	—	+	—	*	—	—	—	—	—
	ERICSSON	22	—	—	—	—	O	O	O	—	—	—	—	—	—	—	+	*	*	*	—	—	—	—	—	—	—
	GORMONT	23	—	—	—	—	*	O	—	—	—	—	O	—	—	—	+	*	—	—	—	—	—	—	—	—	—
	JOHNSON	24	—	—	—	—	—	O	—	—	—	—	*	—	—	—	O	—	*	—	—	—	—	—	—	—	—

* GOOD CONSIDERATION. + APPROXIMATE. O VERY APPROXIMATE. Δ BEING DEVELOPED. — NOT MODELLED.

TABLE 1 (AMENDED AS PER ADDENDUM)

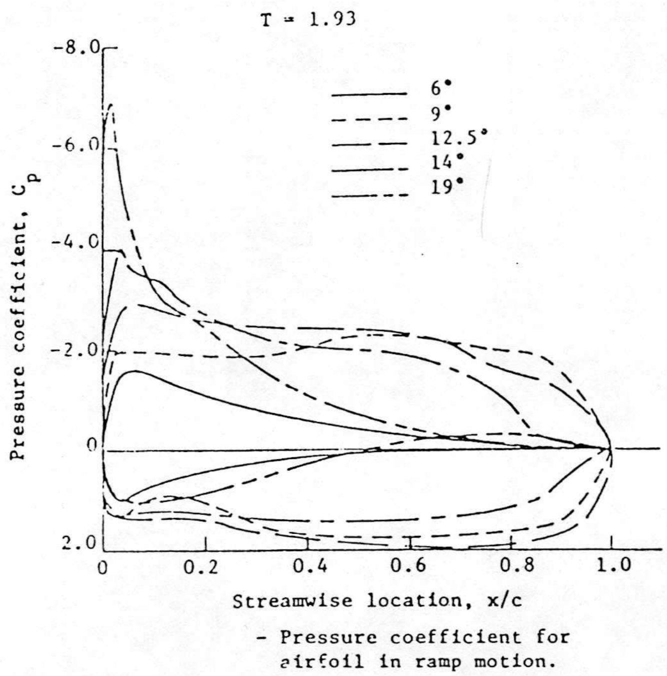


Lift coefficient, R = 10^4, k = 0.25.



Moment coefficient, R = 10^4, k = 0.25.

FIG 1 NAVIER-STOKES METHOD
(LAMINAR FLOW, METHA. REF 7)



- Pressure coefficient for airfoil in ramp motion.

FIG 2 NAVIER-STOKES METHOD
(TURBULENT FLOW, SHAMROTH)
REF 8

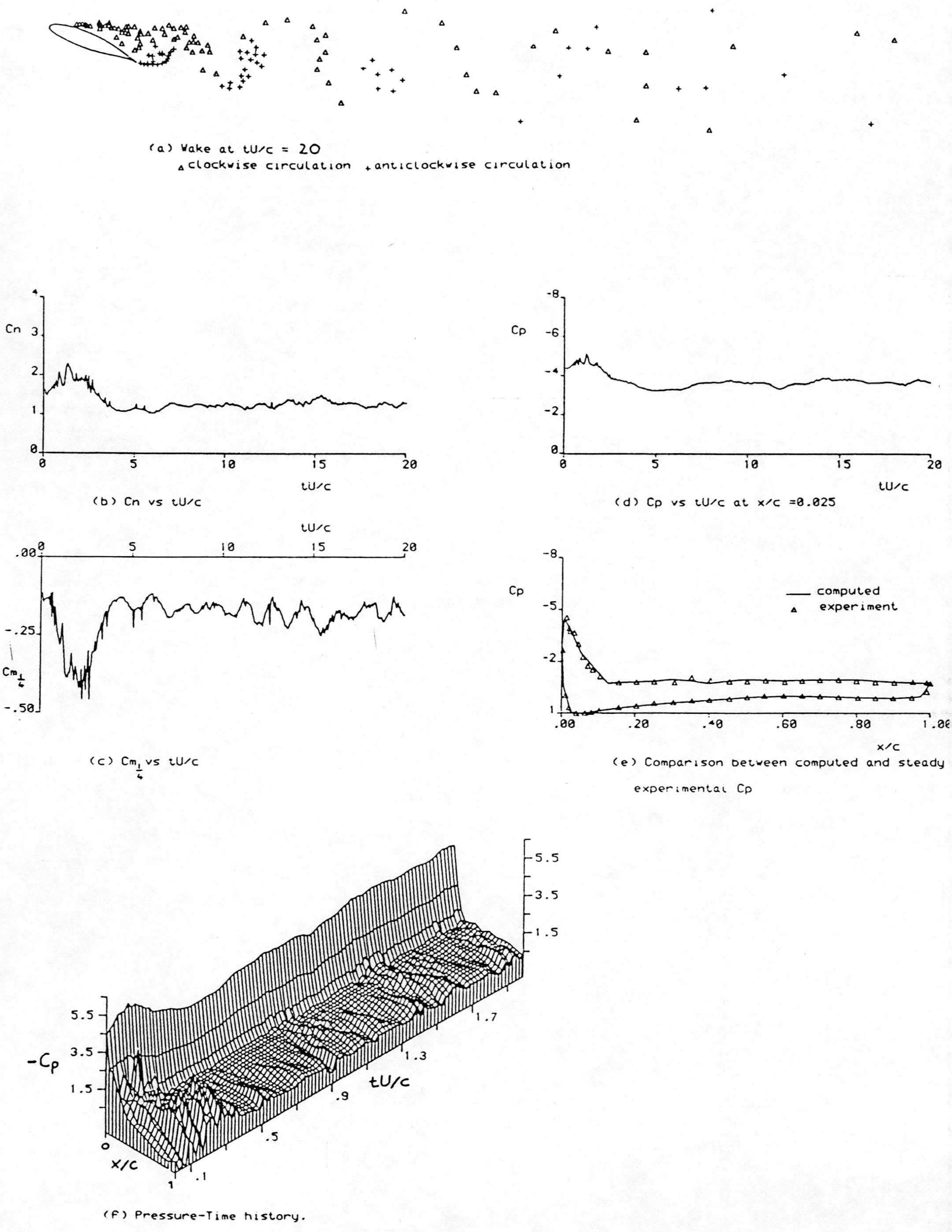
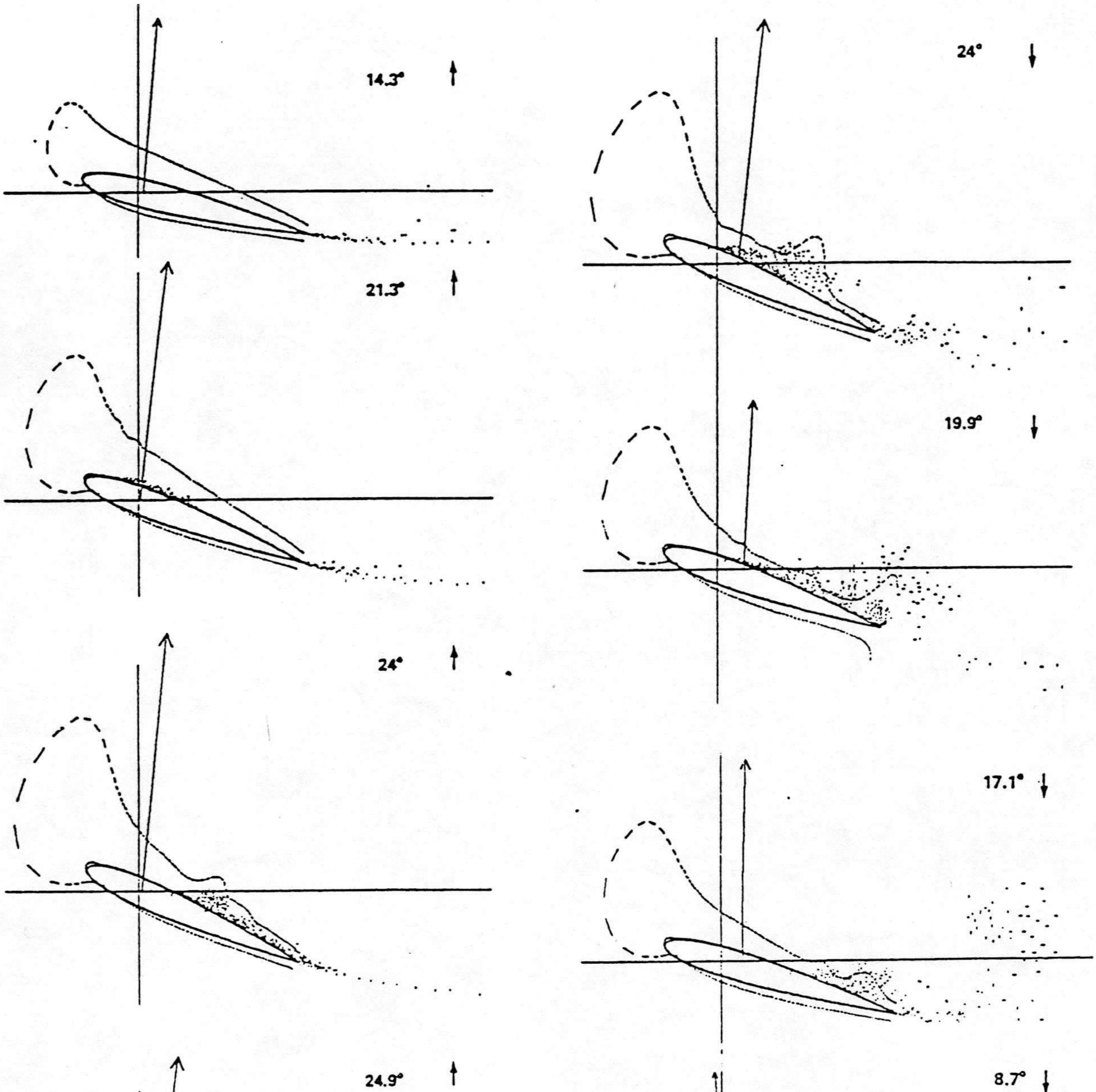


FIG 3. RESULTS OBTAINED FOLLOWING A STEP CHANGE IN INCIDENCE FROM 0-21.14 DEG. USING THE GA(W)-1 AEROFOIL

(REF 11)

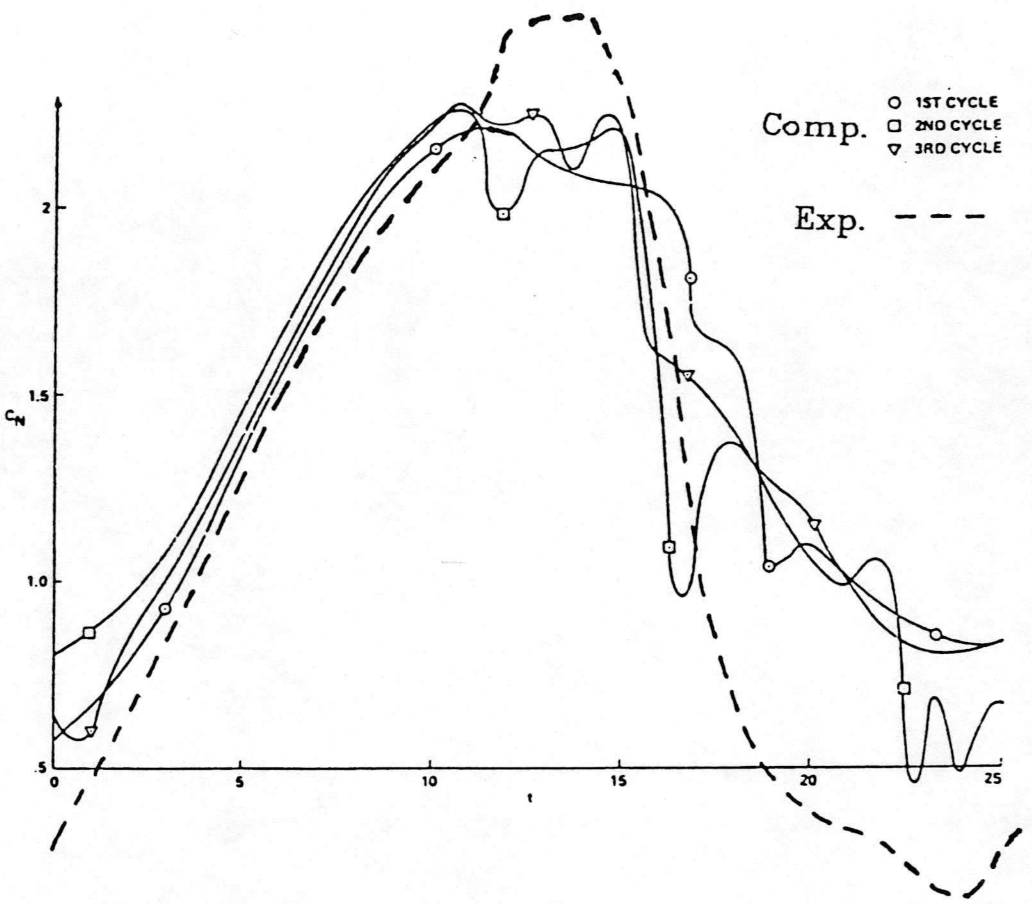


Stills of the Dynamic Stall Simulation

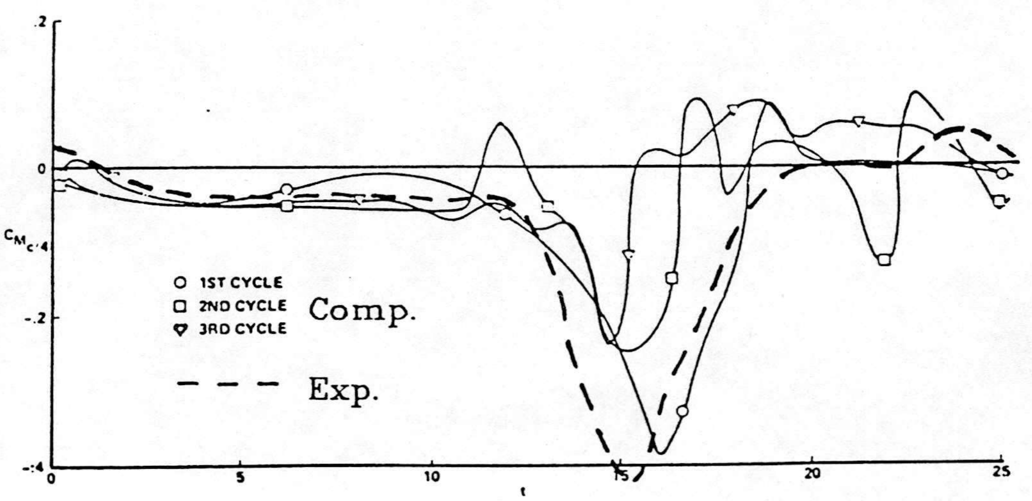
FIG 4a DISCRETE VORTEX METHOD

SPALART ET AL REF 12

(NACA 0012 [illegible])



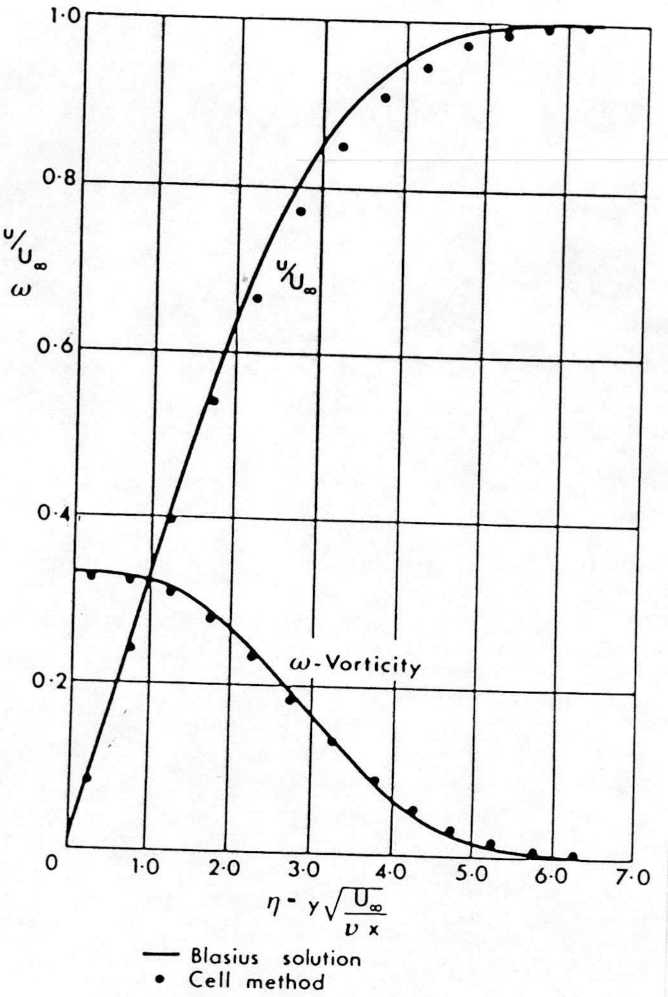
Normal Force Coefficient during Dynamic Stall.



Moment Coefficient during Dynamic Stall.

FIG 4b DISCRETE VORTEX METHOD

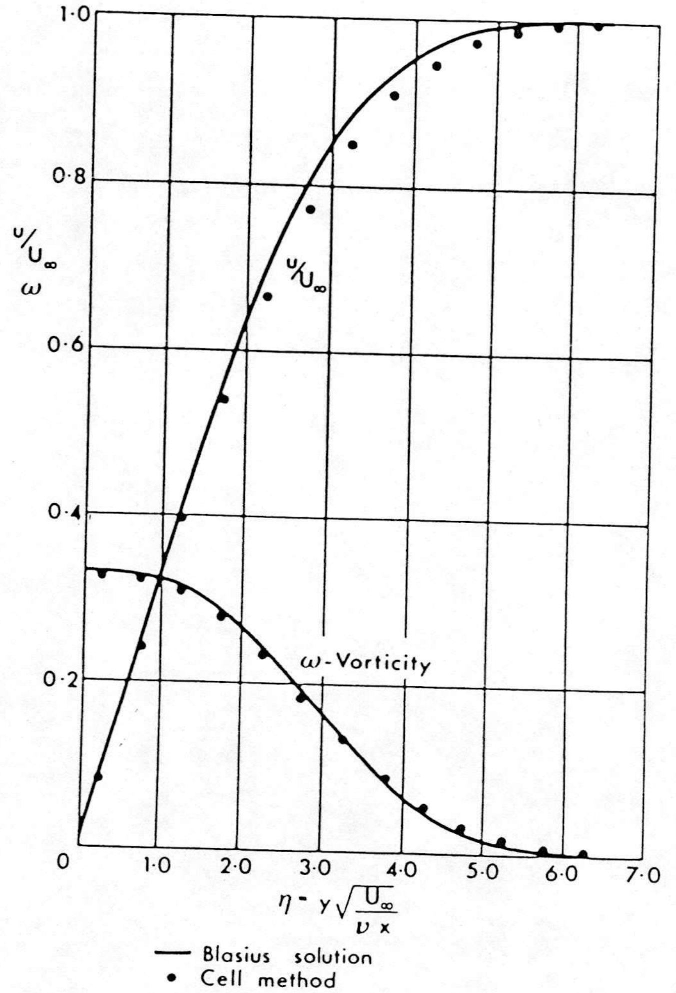
SPALART ET AL REF 12



-Flat plate constant velocity boundary layer.

FIG 5 LEWIS & PORTHOUSE

REF 13



-Flat plate constant velocity boundary layer.

FIG 5 LEWIS & PORTHOUSE

REF 13

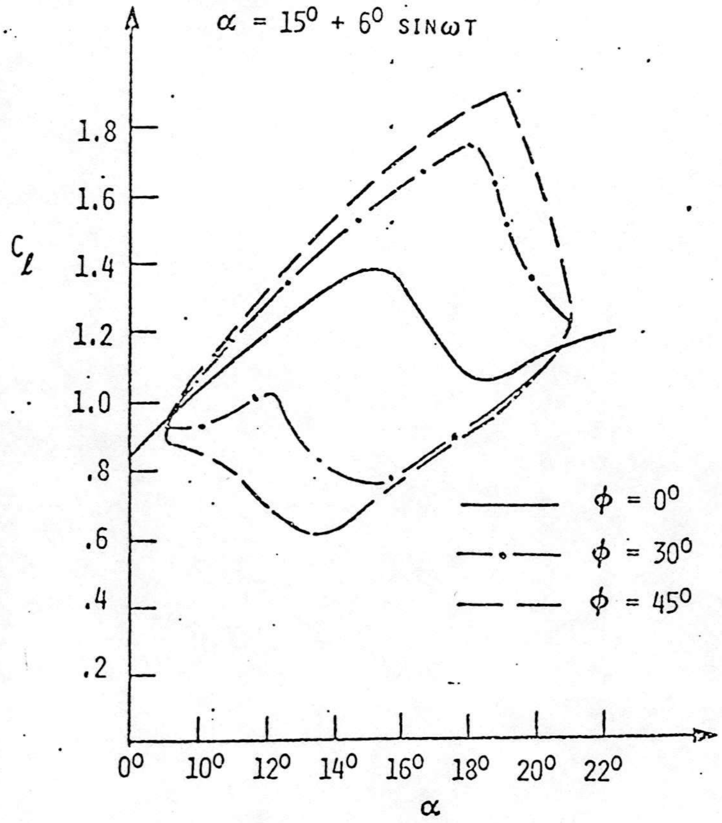


FIG 6 ZONAL METHOD, RAO ET AL* REF 16

* SEE ADDENDUM

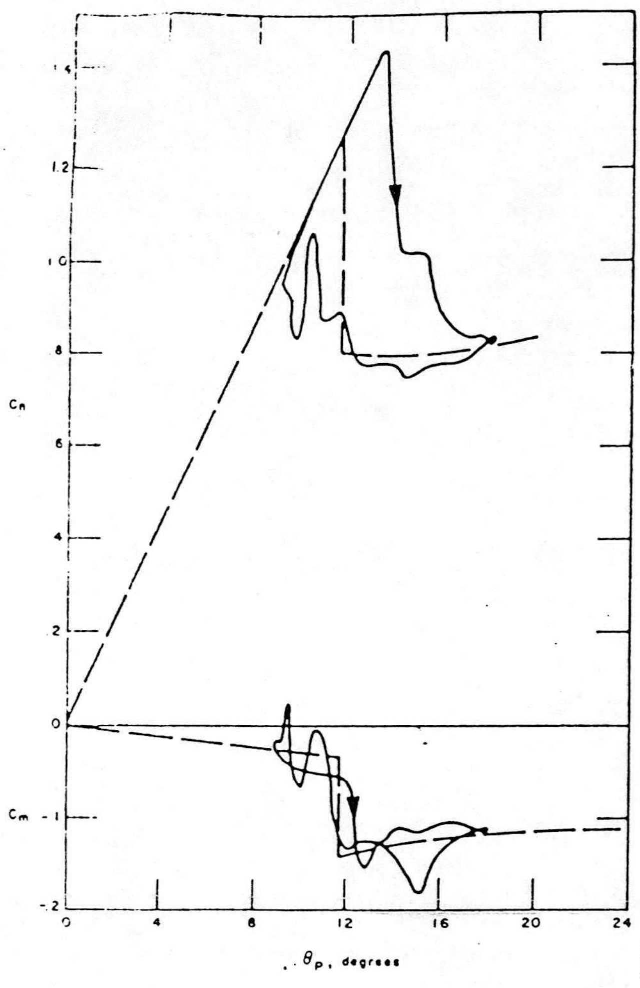
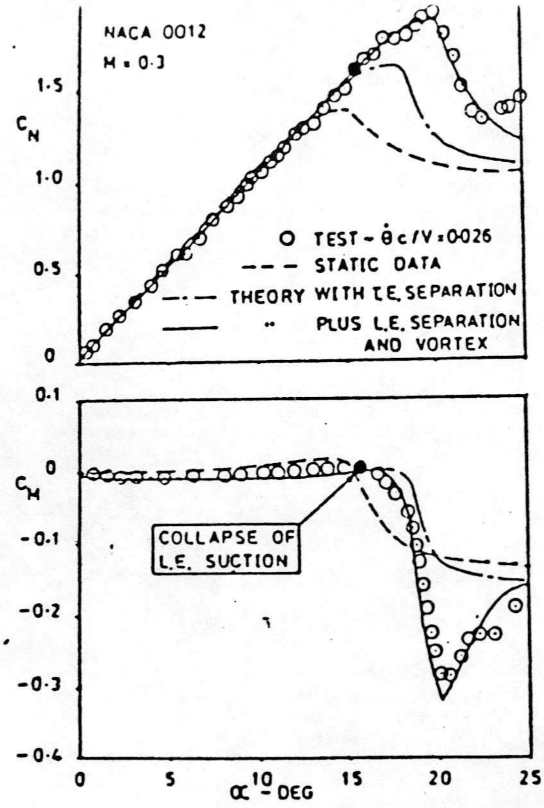
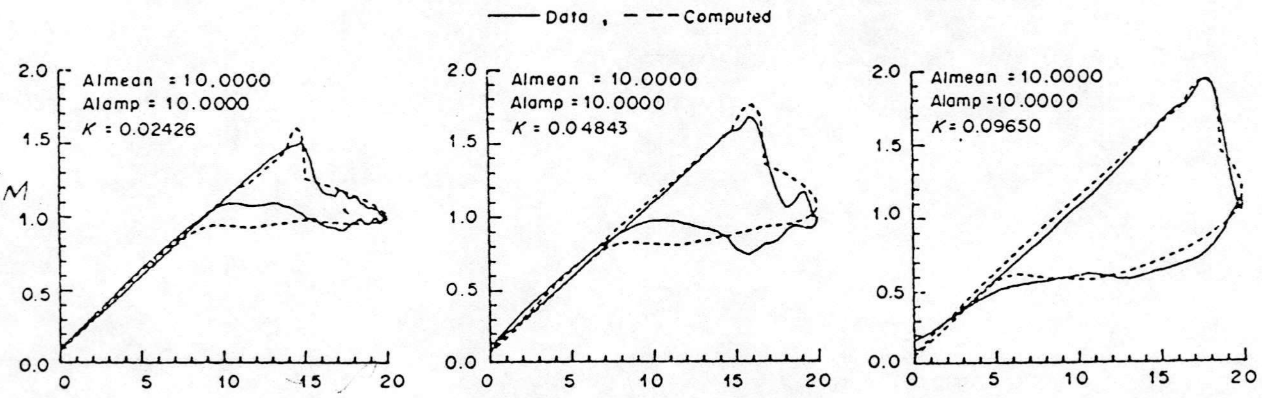


FIG 7 ZONAL METHOD, CRIMI & REEVES REF 18



RESPONSE TO RAMP FORCING

FIG 8 BEDDOES REF 19



NLR-1 AEROFOIL , M = 0·3 , Re = 3·8 ×10⁶

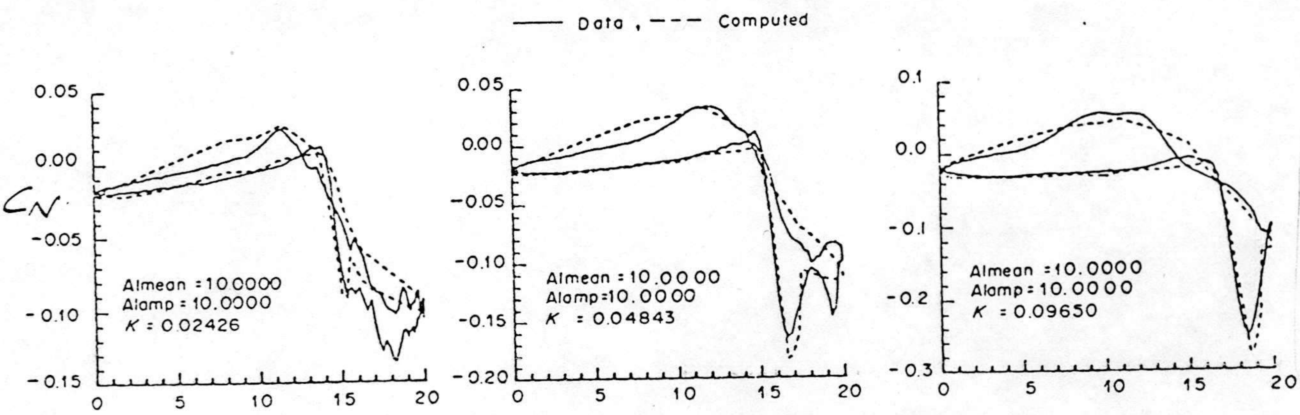


FIG 9 GANGWANI REF 20

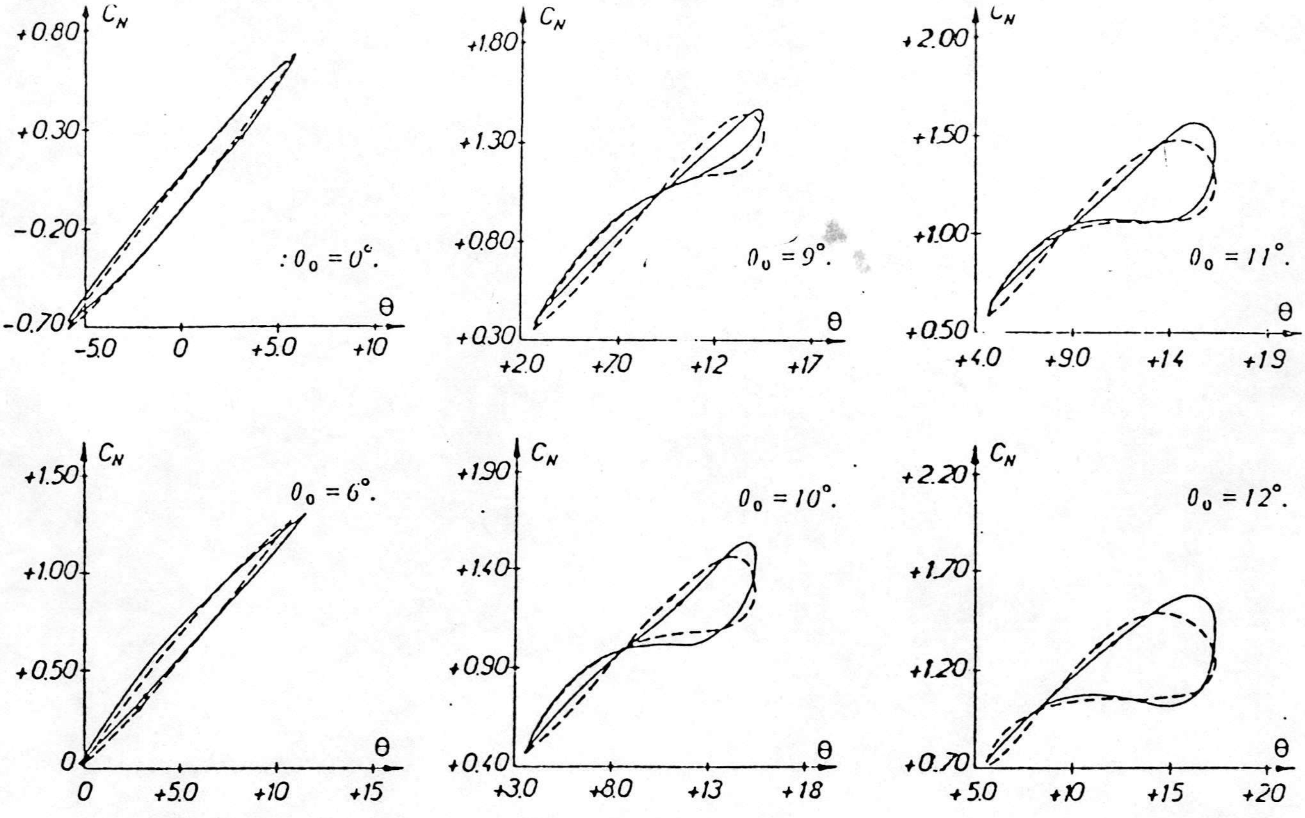


FIG 10 TRAN & PETOT REF 21

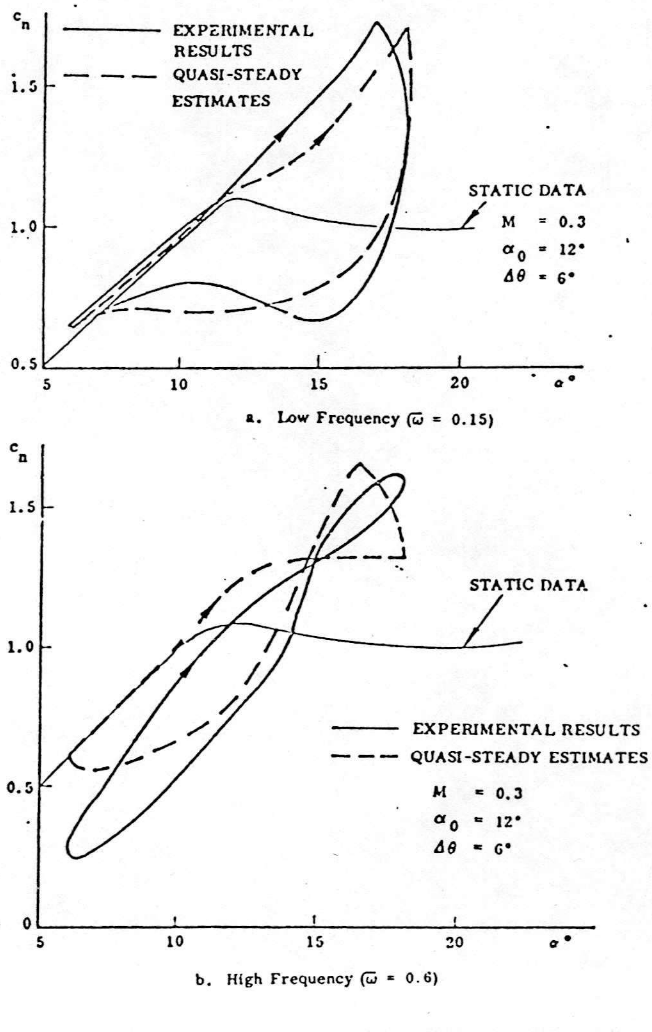


FIG 11 ERRICSON & REDING REF 22